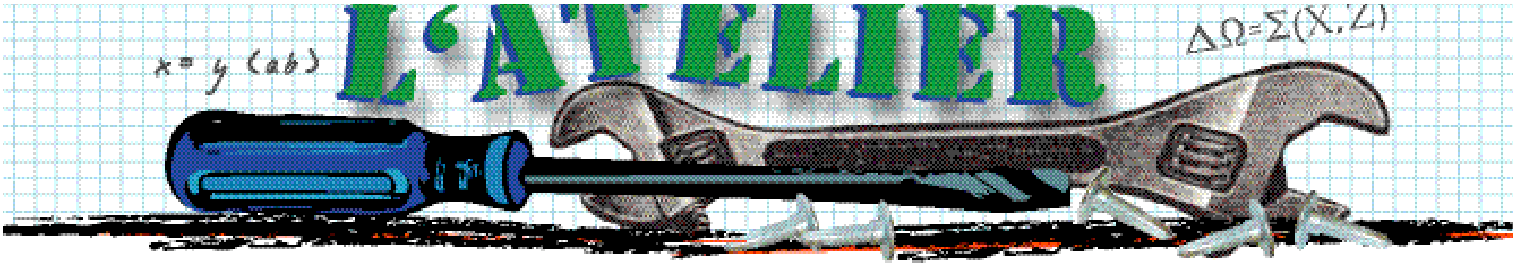


ENGINE CHOICES

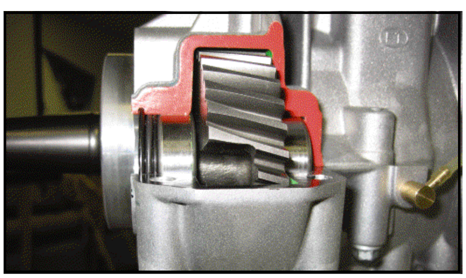
By Kevin Cameron

A growing part of the cost of a new snowmobile now pays for compliance with government-mandated exhaust emissions, noise, and safety standards. While expensive, this is not wrong, for civility requires that our sport meet appropriate social standards. We now face EPA 2006 standards. Fortunately, meeting them is a matter of implementing already well-understood technologies, offering choices in how to meet the new standards. Both two-strokes and four-strokes will qualify handily.

SNOWMOBILE-SPECIFIC DESIGN CONCERNS

Snowmobiles impose special conditions on engine design. Recent sleds ride high on longer-travel suspension. To prevent ski-lifting during hard cornering, everything in their construction must have a low center of gravity – engine included. Because aluminum chassis crack when exposed to intense vibration, the choice is either heavier chassis or smoother engines.

There's no way to fully balance the shaking force of a piston, moving back and forth in a straight line, by placing counterweights on a rotating crankshaft. Therefore makers balance 50% of the shaking force with a counterweight and try to make the motions of two or more pistons in some way cancel each other.



Balancer system used in the Rotax 995.

Two-stroke twins (with their 180-degree timing) give the appearance of balance, for one piston rises as the other falls. But because the two shaking forces cannot act along the same line, the result is a rocking force that becomes stronger the farther apart the two cylinders are. In the largest 180-degree two-stroke twins, the rocking is so strong that it must be canceled by balance shafts.

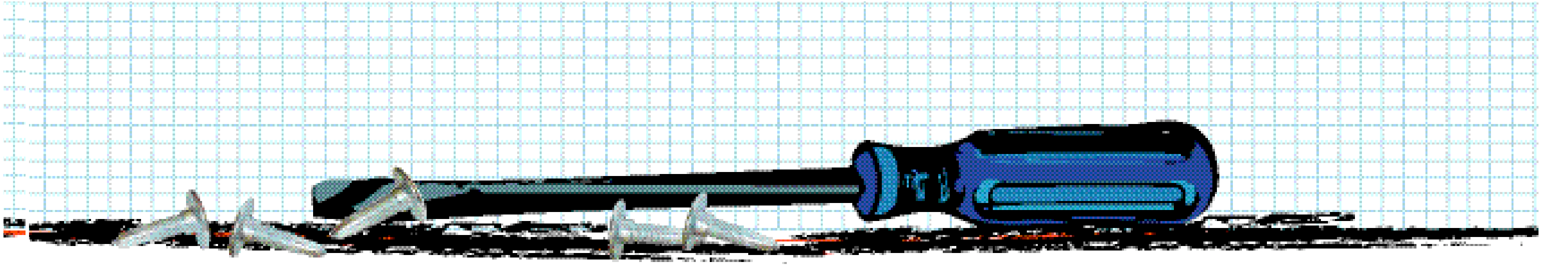
An in-line four-cylinder engine such as Yamaha's Genesis Extreme and 150 FI four-stroke is essentially two 180-degree twins set end-to-end so that their rocking motions cancel. A small secondary (at twice crank speed) horizontal shaking remains. When in-line fours are made large, their piston mass may require a system of secondary balancers.

In-line triples rock much as 180 twins do, and can be smoothed by a balance shaft or be rubber-mounted. 90-degree V-engines can achieve primary balance easily, but even smoother are the "flat" or boxer engines, like BMW (motorcycle) twins or Honda's Gold Wing fours and sixes. Flat engines also have desirably low CG. Vee and flat engines require more than one cylinder head, each with its own cam drive, cams, valves, &c. This duplication adds cost, complexity, and weight.

90 degree V-4 engine found in Honda VFR 800 motorcycle.

Light weight is better than heavy on the snow - unless all operation will take place on groomed trails. That means that the total weight of the engine, its cooling system, and the fuel it needs are important to performance – especially in deep powder. Two-stroke engines are compact and their heaviest part is the crankshaft, mounted fairly low in a sled. Four-strokes that are mounted upright, automobile fashion, have much of their considerable mass up high, in the cylinder head, which is full of heavy steel parts such as cams, gears, springs, and tappets. For equal power, engineers have estimated that a four-stroke requires about 40% more mass and bulk than a two-stroke.

Snowmobile belt CVT drive systems are well adapted to the frequent pulsing of two-stroke twins and triples or four-stroke fours. For two-stroke twins and triples at 6500-rpm the pulsing is at 200-300 pulses per second. For a four-stroke four at 7500 or 10,000-rpm the numbers are 250 and 333 pulses per second. For a 4-stroke twin at 6500 or 7500-rpm, the numbers drop to 108 and 125 pulses per second. The larger and less frequent the pulses,



the shorter the life of conventional belt clutches. Some form of spring drive or damper may solve this problem, but it demands consideration.

TWO-STROKES

Snowmobiles began with light, simple two-stroke engines, which fire every time a piston comes to TDC rather than every other time as in four-strokes. A two-stroke's exhaust and fresh-charge valving is performed by its pistons, sliding past ports cut in the cylinder walls. By contrast, a modern four-stroke has mechanically-operated valves located in the cylinder head, driven by one or more camshafts. The two-stroke is lubricated by total-loss oiling, either mixed into its fuel or injected by metering pump, so it lacks the four-stroke's oil sump or tank, pressure and scavenge oil pumps, possibly an oil cooler, and connecting pipe work.

The traditional two-stroke's major drawbacks are (1) heavy fuel consumption (in carbureted engines), (2) the difficulty of cooling its (heated-twice-as-often) pistons, (3) its off-season susceptibility to internal rusting, and (4) a relatively narrow powerband, resulting from reliance upon tuned exhaust pipes for much of the engine's pumping. A carbureted two-stroke burns a lot of gas and has high unburned hydrocarbon emissions (UHC) because (1) its cylinders are scavenged with fuel-air mixture, not pure air, and (2) exhaust and fresh-charge ports are open together for 1/3 of every revolution. The fresh charge that short-circuits out the exhaust during this time is the problem.

Increasingly in new designs the carburetor is replaced by DFI (Direct Fuel Injection) straight into the combustion chamber, or by SDI (Semi-Direct Injection), which injects into a part of the air stream that cannot reach the exhaust port before closure. Either way, the loss of charge out the exhaust is stopped. DFI or SDI engines now routinely achieve emissions and fuel consumption levels as good as or even better than those of four-strokes. Because DFI/SDI engines have so little UHC in their exhaust, meeting even stricter future emissions levels will be a simple matter of adding an exhaust catalyst. For 20 years pundits announced that the two-stroke engine was finished. It is now proven that advanced DFI/SDI two-strokes can match the best four-strokes in fuel consumption and emissions control, so it's likely they will be with us for a long time to come. Yet even DFI/SDI brings with it special problems that must be addressed. One is that with no evaporating fuel passing through their crankcases, coolant may have to be circulated through them to keep temperatures in check.

Two-stroke pistons are aggressively cooled to offset their double-time exposure to combustion heat. New designs send coolant first to the cylinders, making cylinder walls as cool as possible. To move piston heat to the cooled cylinder walls, increasingly thick crowns provide a generous heat path. Piston weight is not a problem for two-strokes because they need not rev as high as four-strokes do to produce their power.

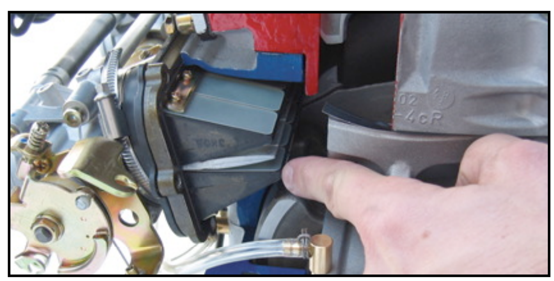
Two-strokes are lubricated by metered delivery of oil into the crankcase, after which it is swept by engine airflow into the cylinders and burned. Because a two-stroke's crankcase is used as a charge pump, it cannot be sealed and lubricated by circulating oil as a four-stroke's bottom end is. Metered delivery proportions oil to throttle opening and rpm, so that a modern two-stroke's oil consumption is quite comparable with that of a four-stroke. Smoky two-stroke exhaust is rapidly becoming a thing of the past. The development of cleaner burning oils is also contributing to clean up this situation. Rusting of rolling bearings or piston rings can occur if the machine is stored without normal precautions.

TWO-STROKE TYPES

The simplest two-strokes use the piston for all valving tasks. Because a piston-controlled intake port has as much timing ATDC to blow out intake as it has BTDC to draw it in, the system depends on the inertia of fast-moving intake flow to work at all. Although good power can be made this way, bottom power is always weak because of back-pumping.

Use of a cut-away rotating disk as an intake valve allows unsymmetrical timing to be used, doing a better job of combining mid- and top power. Rotary-valve engines, however, cannot be reversed. It is also difficult to provide disk valves for more than two cylinders on a single crankshaft.

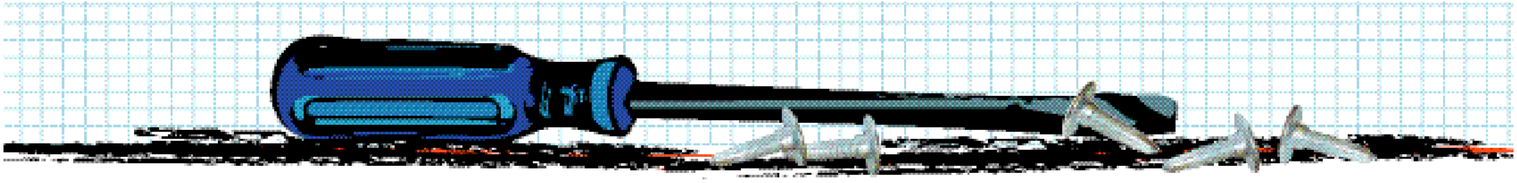
Disk was long the ultimate induction (for power output) but Honda in 1982/83 showed that large-area reed valves could deliver equal power. Reeds are simple spring-like flapper valves of thin steel or composite, that are pushed open by a pressure difference and close when that pressure difference reverses. Reed engines are reversible and reeds can be designed into just about any cylinder configuration.



Reed valves used in Fusion 900 engine.

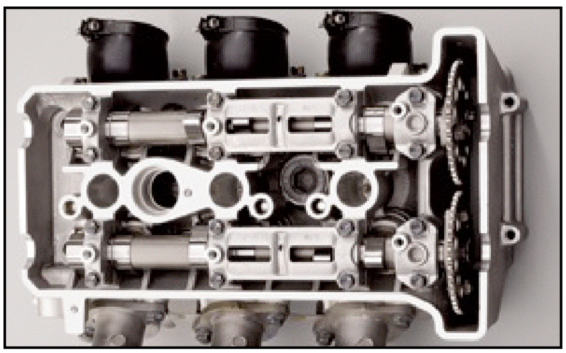
FOUR-STROKES

Four-stroke engines power most of the world's vehicles so years of R & D make them very durable. They are economical because their pumping is mostly of the positive displacement kind – the four separate strokes effectively separate fresh charge from exhaust. Their pistons are well cooled and they are lubricated by pumped, filtered, recirculating oil systems. On the downside, their major problems are extra bulk and



weight, heightened manufacturing costs and the fact that they often require electric starting. Their intense combustion generates nitrogen oxides (NOx), the most difficult emission to clean up.

Four-strokes have evolved from lawnmower-like side-valves (two valves beside the piston, their stems downward) to overhead valve (OHV) with two valves above the piston, stems upward. Placing valves above the piston not only eliminates the inefficient bends in a side-valve's ports, but also reduces combustion chamber surface area, cutting heat loss and making it easy to use torque-boosting higher compression ratios. Overhead valves can be operated either by pushrods and rocker arms, driven by a cam located close to the crankshaft, or by placing one or two cams above the valves (Over Head Cam, or OHC). Typically, a single cam (SOHC) operates the valves through rocker arms, while dual overhead cams (DOHC) act through either inverted-bucket tappets or finger followers.



Genesis 120's dual overhead cam (DOHC) arrangement.

Pushrods and rockers are cheaper but OHC, by eliminating the extra mass of pushrods and rockers enables the valve train to either follow cam profiles at higher rpm, or permits cam events to be made shorter in the interest of a wider torque curve. Modern four-strokes have multiple valves per cylinder, their stems angled apart only slightly. This yields a compact, fast-burning combustion chamber with low heat loss, with straight, high-flowing ports.

Because four-stroke combustion pressure hasn't increased much in 50 years, the main path to higher power is through higher rpm and lower friction. To achieve this at survivable piston accelerations, bores have grown larger and strokes shorter. Reciprocating parts have been made steadily lighter and bearings smaller.

Four-strokes have a special efficiency problem – pumping loss. When running on part-throttle, each intake stroke pulls a partial vacuum in the cylinder and this appears as a power loss. Two-strokes, with more equal pressures above and below their pistons, have lower pumping loss.

THE NATURE OF FOUR-STROKE POWER

Because a four-stroke behaves more like a piston air pump, while a two-stroke relies on wave action in its exhaust, the four-stroke can fill its cylinders with a fairly full charge of mixture across a wider range of rpm. Good cylinder-filling means high, constant torque, and this is what gives four-stroke engines their broad pulling power.

The harder we work to increase four-stroke power, the more it resembles a two-stroke in its power characteristics. Longer valve timings and increased reliance on intake and exhaust wave action can cause a four-stroke's torque curve to develop sharp peaks and valleys.

TORQUE VS. TORQUE-Y

What is torque? To an engineer, it is a twisting force, so an engine's torque is the continuous twisting force it can deliver at any given rpm. But to a rider, "torque" has come to become synonymous with a subjective feeling – the ability to accelerate no matter what rpm the engine is turning – high, medium, or low. This torque-y feeling is the very opposite of peakiness.
Using the engineers' definition, let's compare two-stroke and four-stroke on a torque-per-liter basis. Torque is a direct result of the stroke-averaged combustion pressure acting in an engine. The best two-strokes can deliver a stroke-averaged combustion pressure of 180-200-psi, while top four-strokes can edge that up to 230-psi. Yet because the two-stroke produces torque every time a piston comes near TDC instead of every other time as in four-strokes, the two-stroke produces 150-170 lb-ft of torque per 1000-cc of engine displacement, while the four-stroke produces 75-95 lb-ft per 1000-cc.

How can this be? Four-strokes are "torque-y", while two-strokes are peaky. But no, we are comparing the engineer's and the rider's meanings of the word "torque". Two-strokes produce more "engineer torque" per displacement than four-strokes, but they do it across a much narrower percentage of their rpm band. A four-stroke of moderate performance can pull well across 75% of its rpm, but a two-stroke's stronger torque exists in a much narrower range of 25-30%. The two-stroke excels in torque but the four-stroke excels in range. Yet as the four-stroke is tuned to higher power levels, its pulling range also narrows. Mother Nature is stingy – she will give us some over a wide range, or a lot across a narrow range, not both! The relative narrowness of a two-stroke's power is not a problem because snowmobile belt CVTs were originally developed for two-strokes.

High torque explains why two-strokes remain popular in snowmobiling and continue to be developed – they can with few parts generate the force to move heavy sleds from a smaller, lighter package. Four-strokes can do the job too, but it takes more steel and aluminum to get it done.

FUEL CONSUMPTION

Let's compare fuel consumptions, using the amount of fuel that must be burned to produce one horsepower for one hour as our standard:

Carbureted two-stroke: 0.65 – 0.7 lb/hp-hr
Four-stroke (either carbs or FI) 0.5
Two-stroke with DFI/SDI 0.45 – 0.5
Diesel 0.35 – 0.38

It is relatively easy to meet emissions standards with a moderately tuned four-stroke because each of the four engine functions – intake, compression, power, and exhaust – has a separate stroke. Harder to deal with are the nitrogen oxides (NOx), whose production is increased by higher combustion temperatures. Two-stroke combustion is cooler by reason of inert residual exhaust which can never be entirely eliminated. When four-stroke power is increased by the usual hot-rod techniques, emissions can rise because longer cam timing increases the time during which both exhaust and intake valves are slightly open together, permitting fuel to short-circuit, creating unburned hydrocarbon emissions that are similar in nature to a traditional two-stroke.

NOISE

When it comes to noise, four-strokes have it easy, for sound energy increases with frequency. A four-stroke's exhaust valves begin to open from zero speed, while the two-stroke's piston at exhaust opening is at maximum speed. The faster the opening rate, the more high frequency in the sound produced. This gives the two-stroke sound its sharpness. Many people find the four-stroke's "motorboat sound" pleasing. Engineering can make either type conform to mandated sound levels – there are no mysteries here.

FUTURE ENGINE DEVELOPMENT

Horsepower is computed from three major variables – displacement, rpm, and net, stroke-averaged combustion pressure. Because two-strokes are mechanically simpler and turn lower rpm than four-strokes, it is easier for them to adopt larger displacement – and this has been a long-running trend. Four-strokes gain more weight when enlarged, and they are already not light.

Increases in rpm are complicated on the snow by the limitations of belt clutches (CVT systems become increasingly inefficient as rpm rises), but higher rpm is the special province of four-strokes. Consider that there is now on the market a four-stroke motorcycle engine red-lined at 17,500, an operating range once the exclusive domain of Formula 1 race car engines!

The engine in the 2006 R6 has a 17, 500 rpm redline!

Due to the aforementioned clutching constraints, higher revolutions require the use of a speed reducer, and power gearing is never cheap. Likewise, making four-strokes reliable at high rpm requires expensive, fatigue-resistant component – pistons, connecting rods, valves, springs, and tappets. Such costs will make power boosting via turbocharging or supercharging attractive, because of its potential for increasing combustion pressure without resorting to excessive rpm.

As friction loss increases roughly as the square of rpm, a long-running trend is the reduction of parts weights. Pistons have dwindled away to mere "ashtrays", con-rods are now very slender, often forged and surface-hardened, and valves are beginning to be made of titanium, which weighs 40% less than steel. Loss from crank plain bearings increases as the cube of diameter, so crank journal sizes are reduced until the crank is just strong enough to provide the desired lifetime. Other sources of high speed loss are in the crankcase, where air displaced by one descending piston must pass down through the fast-spinning crank and into the space below, then up through the crank again to fill the void created by another piston's rising. To prevent this loss of several hp, large holes are now pierced through the upper main bearing webs or the sides of the cylinders themselves, to give this air a shorter, lower-drag pathway. Although short-duration, rapid-lift cam profiles give the widest and strongest powerband, significant losses created by very high cam-to-tappet friction may arise, and must be considered.

It was once believed that air-cooling saves weight, but when performance is high, masses of metal are needed to conduct combustion heat to cooling fins. Cooling water weighs only 1/3 as much as any solid aluminum heat path it replaces!

WHAT LIES AHEAD

Further development of two-strokes will likely take the form of transforming them into the efficient, low-emissions powerplant that the auto industry envisioned during its short romance with the type in the early 1980s. Low mechanical and pumping losses, combined with the increasing sophistication of DFI/SDI promise success here. Emissions authorities were strongly impressed by Bombardier's E-TEC DFI when it was barely out of prototype. What will they think once its performance is fully optimized?

Makers committed to four-strokes must hope that smaller-displacement and hence lighter but super/turbo-charged engines may deliver two-stroke-like power density and wide, usable torque. In the past, when larger, slower-turning, and lower stress engines have competed against small, complex, and highly supercharged opponents, the victory has gone to the simpler type. The challenge then will be to develop four-strokes specifically for snow use, with all of the virtues (low center of gravity, moderate cost, high power density, and good reliability) sought by snowmobilers.

If we draw on the experience of the motorcycle industry which was faced with a very similar situation almost 30 years ago when EPA standards were first introduced (in 1976), a close look at the current crop of motorcycles clearly illustrates that performance and cleaner emissions can co-exist. Despite rampant rumours at the time about a future full of heavy and under-performing bikes, new motorcycles such as the R1, GSX-R's and others have proven these fears to be ill-founded. Technological developments have come to the rescue of the motorcycle industry and will surely do the same for snowmobiling. Stay tuned.